Geomagnetic Storms and Wintertime 300-mb Trough Development in the North Pacific-North America Area

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ABSTRACT

This study confirms, for seven additional winters, a relationship discovered earlier between geomagnetic storms and subsequent deepening of 300-mb troughs. For this study a trough which moves into or is formed within the Gulf of Alaska area on the second to the fourth day after a geomagnetic storm, is defined as a key trough; it is found that key troughs tend to undergo a greater degree of subsequent intensification than non-key troughs. A vorticity index is computed in addition to the trough index used in earlier studies, and both indices show the same tendency. In the final section we speculate on possible causes for the relationships discovered.

1. Introduction

Earlier studies by Macdonald and Roberts (1960) and others showed that wintertime low-pressure troughs near the 300-mb isobaric surface appear to show characteristic deepenings that are statistically related to geomagnetic activity. Troughs that formed over or moved into the North Pacific region (see Fig. 1 for definition of target area) 2–4 days after a bright aurora or geomagnetically-disturbed day tended subsequently to deepen more strongly than those not preceded by such geomagnetic or auroral activity. Similar results were obtained for the 500-mb level by Macdonald and Roberts (1961) and by Twitchell (1963). These findings were obtained mainly near solar maximum No. 19, during the winter half-years of 1956–57 through 1959–60. In addition, some of the 500-mb results were obtained for the period near solar maximum No. 18, in the winters of 1945–46 and 1946–47. Woodbridge (1971) studied similar relationships for a solar minimum period, namely, the winters of 1964–65 and 1965–66. He reports confirmation of the earlier result.

In all the above research, the trough was measured by a trough index I_t, which is essentially the ratio of the trough depth in the north-south dimension to its width in the east-west dimension, with certain weighting factors giving stronger emphasis to closed lows. The troughs were tracked from the time they were formed within or moved into a "target" area defined as the region north of 40N and bounded by longitudes 180° and 120W. They were tracked continuously until they either dissipated or moved east of the 0° meridian. This movement across half a hemisphere characteristically required 1–2 weeks. The troughs were classified according to the maximum trough index achieved any time during their period of observation, and the class limits were adjusted so that one-third of the troughs were classed as large, one-third as medium, and one-third as small, depending on this maximum I_t. Because of the 3-day average lag between the "key day" (or magnetic storm day) and the "0-day" (or the day of first appearance of the trough in the target area), it is possible that a trough could be classed as large, for instance, based on a trough index value that occurred as much as 17 days after the magnetic storm.

Roberts and Olson (in press) have reported results of studies during three more recent winters: 1964–65, 1965–66, and 1970–71. Two years were near solar minimum; one followed by about two years the solar maximum No. 20. For all three years, the conclusions agreed with the earlier results, although for the two solar minimum years, the statistical significance levels fell an order of magnitude or more below those obtained by Woodbridge (1971) for the same period. We have not been able to reproduce Woodbridge's tables independently. The technique of trough indexing used by Roberts and Olson was the same as that used by Roberts and other colleagues earlier, except that the trough index was somewhat simplified in the present

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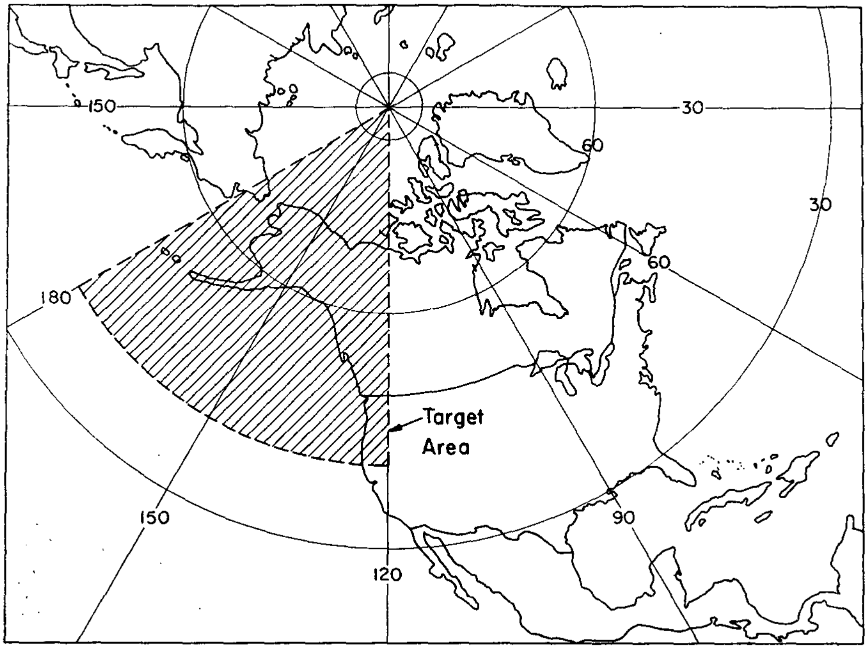

FIG. 1. The target area in the North Pacific region.

work. In all earlier work, the index was defined in such a way as to give closed lows greater weight, but this weighting factor was eliminated in our recent study.

The most important improvement in our recent study was that we used, in addition to the trough index, a new index based on objectively-derived measures of absolute vorticity at the 300-mb level. The vorticity index and the trough index gave similar results, and, as Fig. 2 shows, both indices confirmed the earlier results. The principal difference was that the use of vorticity data gave a maximum effect slightly earlier in the trough life. By the trough index technique, we found that the "key troughs" (i.e., the troughs whose 0-day followed a geomagnetic key-day by 2, 3 or 4 days) reached a maximum compared to "non-key troughs" approximately 4 days after 0-day, in agreement with previous results. When we used the vorticity index, this maximum difference came approximately 2 days after 0-day. This effect can be seen by comparing Fig. 2a with 2b. Since the vorticity index can be measured objectively, is more physically meaningful, and lends itself more readily to computer use, we will probably use only the vorticity index in future work.

Since the discovery of a relationship between geomagnetic storms and 300-mb troughs is not one that

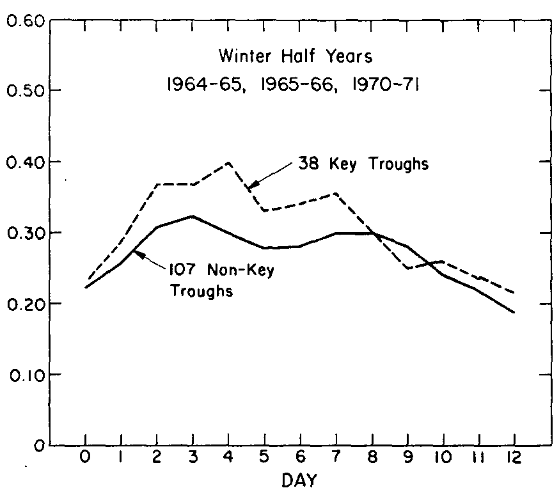

FIG. 2a. Mean trough index I_t vs days after 0-day, for the winters 1964–65, 1965–66, 1970–71.

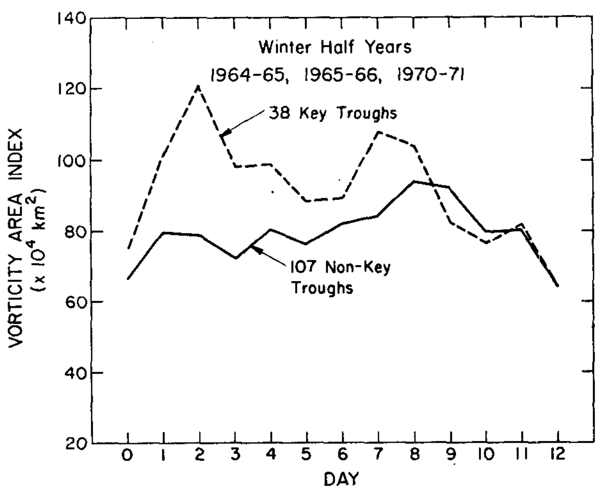

FIG. 2b. Mean vorticity area index vs days after 0-day, for the same years as in Fig. 2a.

could be expected based on any present dynamical theories of trough development, we have concluded, in concert with others, that a 20-year study covering the years 1950–70 should be attempted, and that for it we should use a consistent method of analysis throughout. The present report encompasses seven years of that study, which is still in progress.

The results discovered earlier, and also those reported here, are of sufficient importance and scale to merit attention on the part of workers interested in improving future forecasting methods, and are also sufficiently striking to command the attention of researchers concerned with exploring possible mechanisms for the deliberate or inadvertent modification of large-scale features of the lower stratospheric circulation. However, the results are perplexing, in that there is no plausible physical explanation of them, and also because certain studies from which one might expect positive findings if our results are valid, have nonetheless failed to reveal them. For example, Stolov and Shapiro (in press) have made a highly general study of circulation changes at the surface and at 700 mb following geomagnetic disturbances, for 1947–70. They found no significant relationships in either zonal or meridional circulation indices. Added work is urgently needed to reconcile these differences.

2. Procedure of vorticity analysis

The first step in our analysis was to examine the absolute vorticity and pressure-height contour maps for each of the seven winters (October through March) 1964–65 through 1970–71. When a major trough moved into the target area (between 120W and 180° longitude and north of 40N latitude) or was formed in the target area, it was given a number and assigned a 0 date corresponding to its date of first recognition in this

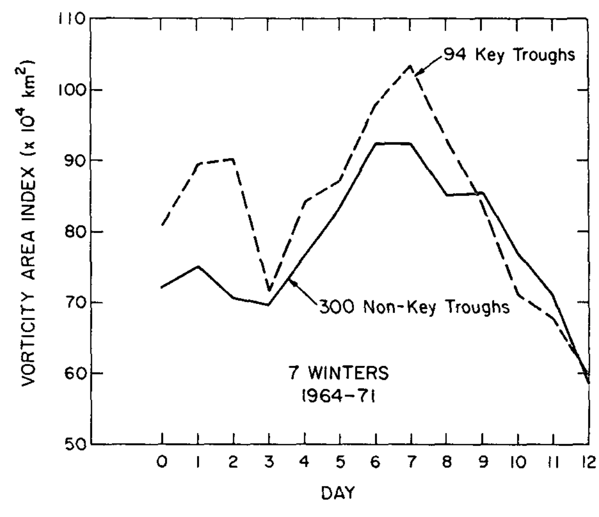

FIG. 3a. Mean vorticity area index for key and non-key troughs, 1964–71.

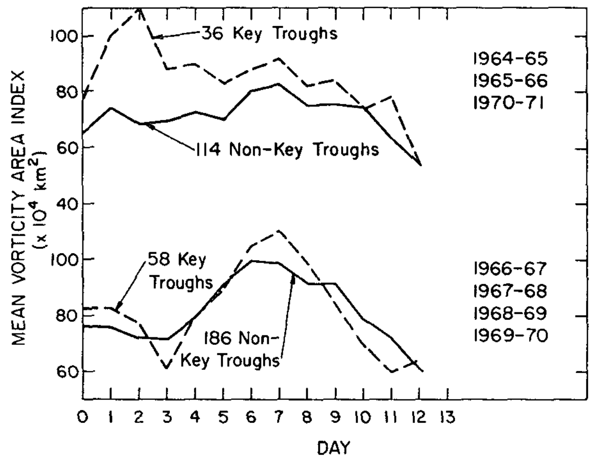

FIG. 3b. Same as Fig. 3a with separate curves for three winters, 1964–65, 1965–66, 1970–71 (top curve) and four winters 1966–70 (bottom curve).

area. Its development history and movement were then followed by analysis of subsequent maps until it could no longer be identified, or until it passed east of the 0° meridian. Both 0000 and 1200 GMT maps were analyzed each day, and the average vorticity index for the two maps for each trough was computed. This average value was considered to be representative of the trough for that day. The vorticity index was defined as the sum of the area (km^2) over which the absolute vorticity exceeded 20×10^{-5} sec^{-1} plus the area over which vorticity exceeded 24×10^{-5} sec^{-1}.

For virtually all troughs there was some area over which vorticity exceeded the lower value, and for the major troughs there was nearly always some area over which the higher value was exceeded. The foregoing procedure generated daily vorticity index values for each trough for each day of its history, which varied from several days to as long as two weeks. The process of identifying vorticity peaks with the low pressure troughs was the most subjective part of the experiment. Both the decision as to which day in the trough history should be chosen as 0-day, plus subsequent decisions as to how the trough should be identified, as it changed shape and orientation, involved subjective judgments. However, since the vorticity maps were machine-generated and required no subsequent analysis save for identifying each trough with a related vorticity maximum, we believe that the objectivity of the analysis is far higher than in the earlier studies.

The second task was to pick the geomagnetic key dates. In earlier studies, such things as sudden commencement geomagnetic storms and photometrically bright auroras were used to define these dates. Our experience has shown that the results obtained in this type of study depend very little on which of several geomagnetic indices we used. In this study, we decided to use daily values of a commonly-employed geomagnetic parameter,[2] A_p, which is generally considered to be a linear function of the severity of geomagnetic activity.

The criterion established for a geomagnetic key day was that the A_p value for the day $\geqslant 15$ and that the increase from the previous day be equal to or greater than the monthly average value of A_p. The person doing the meteorological analysis remained unaware of the dates of geomagnetic-activity peaks while analyzing the troughs, so as to assure an unbiased trough analysis.

3. Results

Fig. 3a shows for the seven years the average trough vorticity for each day after the troughs were first identified in the target area, for two classes of troughs: 1) key troughs, defined as those first identified in the target area 2–4 days after a sharp geomagnetic rise signalled by a geomagnetic key date; and 2) all other troughs during the same period. As can be seen, the geomagnetic key troughs are already larger than the others on the day of first appearance, and this difference increases in the two subsequent days. The fact that the geomagnetic key troughs are larger on 0-day is not surprising, in view of the fact that 0-day follows the geomagnetic storm by 3 days, on the average. A second maximum difference is found at day 7. The first maximum is typically associated with a deepening in the Gulf of Alaska region, followed by a slight filling over western North America, and finally a rejuvenation near the Atlantic Coast, leading to the second and somewhat less certain maximum at day 7.

Most of the average features are also evident in the individual years. Each winter half-year typically yields 50–60 troughs, of which 12–15 are geomagnetic key troughs. The middle years (1966–67, 1967–68, 1968–69, 1969–70), which bracket the solar activity maximum of Cycle 20, exhibit less consistency than the others in regard to the vorticity behavior of geomagnetic key troughs as compared to others. We cannot say with certainty that the effect will always be less marked at solar maximum, however. In the corresponding phases of Cycle 19, as reported in earlier papers, the maximum years exhibited a consistent preferential deepening of geomagnetic key troughs, just as did years farther away from maximum. Even for these middle years of the maximum of Cycle 20, however, geomagnetic key troughs exhibited larger vorticities than non-key troughs in the first few days. Previous trough index analysis, completed before we developed the vorticity index, did not reveal a systematically larger trough index value on the first date of the trough in the key area. The significant differences between geomagnetic key troughs and the other troughs occurred later.

To illustrate the difference in behavior between the central years (1966–67, 1967–68, 1968–69, 1969–70) of the period and the others, Fig. 3b has been prepared.

The upper graph of the figure is for the years 1964–65, 1965–66, 1970–71. It is not quite identical to the curve in Fig. 2, because in Fig. 3 and all subsequent work the troughs were identified by vorticity patterns only, rather than using the trough index as in Fig. 2. The lower curve is for the central years of the period. The difference between key and non-key troughs is much less clear here, but the key troughs tend to stand out in the early days, while the troughs are still over the Pacific, and again around day 7, by which time they have characteristically moved to the Atlantic Coast.

TABLE 1. Number of key and non-key troughs which became large, medium or small, with size determined by maximum vorticity area index achieved by the trough during its lifetime, 1964–71.

		Key troughs	Non-key troughs	Total	Significance
Total (seven years)	Large	37	95	132	$\chi^2 = 3.77$
	Medium	33	97	130	
	Small	24	108	132	$p < 0.17$
		94	300	394	
1964–65	Large	6	9	15	
	Medium	2	12	14	
	Small	4	11	15	
		12	32	44	
1965–66	Large	3	14	17	
	Medium	6	12	18	
	Small	1	16	17	
		10	42	52	
1966–67	Large	9	12	21	
	Medium	5	17	22	
	Small	6	15	21	
		20	44	64	
1967–68	Large	4	14	18	
	Medium	5	12	17	
	Small	2	16	18	
		11	42	53	
1968–69	Large	4	17	21	
	Medium	4	16	20	
	Small	6	15	21	
		14	48	62	
1969–70	Large	5	17	22	
	Medium	4	17	21	
	Small	4	18	22	
		13	52	65	
1970–71	Large	6	12	18	
	Medium	7	11	18	
	Small	1	17	18	
		14	40	54	

[2] A_p is the planetary geomagnetic activity index. The daily A_p index is a linearized worldwide index of geomagnetic activity and is computed as follows: Twelve magnetic observatories ranging in geomagnetic latitude from 63N to 48S (of which 11 are in the Northern Hemisphere) are used. Each station determines eight 3-hr indices per day, on a scale ranging from 0 for no magnetic disturbance to 9 for the maximum disturbance. These are called K-indices. By combining the 12 K-indices for a given period a planetary K_p index is obtained for each of the eight periods. Since K_p is a semi-logarithmic quantity, it is necessary to linearize it. This is done by converting K_p to a_p, with a_p varying from 0 to 400 as K_p varies from 0 to 9. The A_p index then is the average of the eight a_p indices for the day. A_p values used in our analysis were published by the National Geophysical and Solar-Terrestrial Data Center, Environmental Data Service, NOAA, Boulder, Colo.

We next carried out a contingency table analysis to assess the statistical significance of key trough vorticity as compared to other troughs. We did this analysis in two ways: 1) to be consistent with earlier studies we categorized all troughs according to their vorticity maximum at whatever time that value was attained in the first 14 days of the trough's life (results in Table 1); and 2) to exploit our interest in the trough behavior in the immediate days after the geomagnetic rise we characterized all troughs according to their vorticity values averaged over their first 3 days in the target area (results in Table 2).

For both analyses, to be consistent with earlier studies, we separated all troughs into three size classes, large, medium and small, so as to place roughly equal numbers in each class. All seven years were included in both tables; we exhibit, moreover, both the totals and the individual year values.

The Table 1 results show that in all years but one (1968–69) the number of large geomagnetic key troughs exceeded the number of small, and the number of small non-key troughs exceeded the number of large ones.

TABLE 2. Number of key and non-key troughs which became large, medium or small, with size determined by average vorticity area index on days 0, 1 and 2, 1964–71.

		Key troughs	Non-key troughs	Total	Significance
Total (seven years)	Large	45	87	132	$\chi^2=12.137$
	Medium	27	102	129	
	Small	22	111	133	$p<0.003$
		94	300	395	
1964–65	Large	7	8	15	
	Medium	4	10	14	
	Small	1	14	15	
		12	32	44	
1965–66	Large	5	12	17	
	Medium	4	13	17	
	Small	1	17	18	
		10	42	52	
1966–67	Large	7	14	21	
	Medium	6	16	22	
	Small	7	14	21	
		20	44	64	
1967–68	Large	6	12	18	
	Medium	2	15	17	
	Small	3	15	18	
		11	42	53	
1968–69	Large	7	14	21	
	Medium	3	17	20	
	Small	4	17	21	
		14	48	62	
1969–70	Large	6	16	22	
	Medium	2	19	21	
	Small	5	17	22	
		13	54	65	
1970–71	Large	7	11	18	
	Medium	6	12	18	
	Small	1	17	18	
		14	40	54	

TABLE 3. Number of key troughs, U troughs, and "geomagnetically quiet" troughs which became large, medium or small, with size determined by average vorticity index averaged over days 0, 1 and 2, 1964–71. Numbers in parentheses are random expectations.

	Key troughs	U troughs	"Geomagnetically quiet" troughs*	Total	Significance
Large	45 (31)	59 (56)	28 (45)	132	$\chi^2=21.23$
Medium	27 (31)	56 (54)	46 (44)	129	
Small	22 (32)	51 (56)	60 (45)	133	$p<0.0003$
	94	166	134	394	

* "Geomagnetically quiet" troughs are those for which there were no geomagnetic key days in the 10-day period immediately prior to 0-day or on 0-day.

The totals in Table 1 show that the chance occurrence of a departure from random distribution as strong as this is about 17% ($\chi^2=3.77$). This is not highly significant. However, the association is in the same direction of associating consistently larger maximum vorticities with geomagnetic key troughs, as shown in all other studies.

Table 2, confined to average vorticities for the first 3 days of the trough life, is more significant. The totals show that the chance occurrence of a departure from random distribution as strong as this is <0.3% ($\chi^2=12.14$). This is rather convincing confirmation that there is a significant preferential enhancement of vorticity of troughs over the Gulf of Alaska target area 2–4 days after sharp geomagnetic activity rises.

To throw additional light on the relationship, it seemed desirable to modify Table 2 into a 3×3 contingency table, with a third category of trough lying somewhere between key and non-key. Since it seemed possible that a non-key trough which had a 0-day fairly soon after a geomagnetic key day might still be somewhat influenced, even though it did not meet the requirements for a key trough, the following new criteria were established: 1) key troughs were defined exactly as before, i.e., 0-day of the trough came 2–4 days after a geomagnetic key day; 2) the troughs which were not key troughs, but which had at least one geomagnetic key day in the 10-day period prior to 0-day or on 0-day were given the classification U or uncertain troughs; and 3) a new category of non-key troughs was defined to include the additional criterion that no geomagnetic key day occurred on or within the 10 days immediately prior to 0-day. We call these the "geomagnetically quiet" troughs. The result for the 7-year period is given in Table 3.

The results shown in Table 3 suggest that there is indeed an effect of the storm for as long as 10 days or more after the storm. The troughs in the U category show a slight tendency to become large, even though they do not meet the criteria for key troughs. The new category of non-key troughs, or "geomagnetically quiet" troughs, shows a great tendency toward small size. The significance of Table 3 is high, with a χ^2 of 21.23 and a chance probability $<0.03\%$.

4. Possible mechanisms and future study

We regard these findings, overall, as an independent confirmation of the reality of the association of geomagnetic disturbances with significant later developments in the 300-mb circulation. It is of great interest that the time lag between the geomagnetic event and the strongest effect on vorticity is of the order of 5 days, i.e., 3 days (± 1) from geomagnetic event to 0-day, plus 2 days to maximum effect. It seems to us that both short-range and long-range weather forecasting may be benefited by development of a physical understanding of these relationships. When we complete the 20-year (1950–70) study, we will have further evidence as to the reality of the relationships, as well as some information about such things as the solar-cycle dependence, if any.

Regarding mechanisms to explain the findings, we speculate that the geomagnetic control might come about through modulation of the blackbody radiation lost to space over the relatively warm North Pacific during these winter months. If Bremstrahlung x-rays associated with strong auroras (in turn associated with geomagnetic disturbances) produced a significant ion-pair production at levels where temperature and vapor pressure of water were just appropriate, it seems possible to us that cirrus clouds might quickly be formed. We do not have any clear understanding of just how ionizing radiation might produce ice nuclei to stimulate sudden cirrus formation. However, suggestions regarding ion-induced nucleation possibilities have been advanced by Mohnen (1971) and by Vohra (1971), among others. The effect of sudden formation of cirrus above a relatively warm surface, during low sun or darkness, would be to decrease the cooling rate at levels just below the cirrus deck, and the resultant net heating, we speculate, could perhaps induce the type of dynamical responses we observe.

We are encouraged by the fact that the winter of 1970–71 seems to show the dynamical effect in a clear manner, because Nimbus-D satellite infrared data have been taken over the Gulf of Alaska for this period. We hope to analyze these data to ascertain whether there is a significant association between geomagnetic disturbances and an attendant reduction of observed outward flux of radiation to space over these areas. If we discover such an effect, we believe we will have an important clue to the physical processes by which the vanishingly small direct energy inputs of geomagnetic activity to the lower stratosphere can affect gross meteorological processes at those levels.[3]

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[3] *Note added in proof:* Shapiro and Stolov (private communication) have done further work on circulation changes following geomagnetic disturbances. The new work uses 21-day running means to eliminate problems caused by seasonal trends. By this technique they find a significant increase in the strength of the westerlies, occurring mainly in the winter season and best developed in the longitude belt from 90W to 180°, 3–4 days after geomagnetically disturbed days.

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